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The objective of the research performed was: (i) development of electrooptic polymers which are usable in the visible, (ii) use of sol-gel chemistry to improve on processability and bulk characteristics for waveguide applications, and (iii) introduction of multifunctionality by composite approach. These objectives were met. For second-order nonlinearity needed for electrooptic effects, we had great success in the design of new types of chromophores with enhanced X(2) and transparency in the visible. Our unique contributions are: (i) inorganic:organic composites for nonlinear optics; (ii) successful poling of molecular-ionic polymers with high nonlinearity; (iii) novel processing to produce poled sol-gel silica/titania doped with electrooptic chromophores; (iv) planar optical waveguides using sol-gel processing; and (v) combination of electrooptic function with photoconductivi to produce photorefractive polymers woth a figure of merit comparable to that of existing inorganic photorefractive systems. The Langmuir-Blodgett method of film deposition was also investigated. The advantage of this method is that it provides a higher order parameter than a poled structure.

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FINAL REPORT

PROJECT: MULTIFUNCTIONAL HETEROSTRUCTURES FOR PHOTONICS

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ABSTRACT

The objective of the research performed was: (i) development of electrooptic polymers which are usable in the visible, (ii) use of sol-gel chemistry to improve on processability and bulk characteristics for waveguide applications, and (iii) introduction of multifunctionality by composite approach. These objectives were met.

For second-order nonlinearity needed for electrooptic effect, we had great success in the design of new types of chromophores with enhanced $\chi^{(2)}$ and transparency in the visible. Our unique contributions are: (i) inorganic:organic composites for nonlinear optics; (ii) successful poling of molecular-ionic polymers with high nonlinearity; (iii) novel processing to produce poled sol-gel silica/titania doped with electrooptic chromophores; (iv) planar optical waveguides using sol-gel processing; and (v) combination of electrooptic function with photoconductivity to produce photorefractive polymers with a figure of merit comparable to that of existing inorganic photorefractive systems. The Langmuir-Blodgett method of film deposition was also investigated. The advantage of this method is that it provides a higher order parameter than a poled structure.

As an example of inorganic:organic composite structures, we prepared crystalline complexes SbI_3:$3S_8$ which exhibited efficient phase-matched second harmonic, opening up the prospect for a new class of nonlinear optical materials. The new chromophores with large nonlinearities developed under this contract are: (i) diethylamino nitrostyrene (DEANST); (ii) hydroxy and dihydroxy-diethylamino nitrostilbene; and (iii) prodan.

To achieve high $\chi^{(2)}$ and stable electrically aligned films with waveguiding optical quality we have used sol-gel processing and prepared a new composite consisting of diethylamino nitrostyrene (DEANST) doped into a composite of silica and polyvinylene pyrrolydone. The $\chi^{(2)}$ value achieved is $>10^{-7}$ esu. To take advantage of nonlinearities derived from both molecular and ionic contributions, new methacrylate polymers containing the N-alkyl pyridinium salt in the side chain were designed and synthesized. Even though these structures contain counter-ions which can migrate under the influence of applied field, we formulated conditions to successfully pole using corona method. In order to enhance the poling efficiency by reducing the prospect of charge migration, the small counter-ion (I^- or Br^-) of the salt was substituted by a bulky tetraphenylborate (TPB^-) ion. The $\chi^{(2)}$ value of this polymer as determined by second harmonic generation is $\sim 2 \times 10^{-7}$ esu.

Novel composites of a conjugated polymer, poly-p-phenylene vinylene, with V_2O_5 and silica were prepared by sol-gel processing in a 50% by weight composition and tested for optical memory application in the configuration of a two-dimensional grating as well as for their third-order nonlinear optical properties. A 60 fs nonlinear optical response was observed confirming that these composite materials can provide fastest optical switching.

In order to use mixed layer Langmuir-Blodgett films for nonlinear optics, we have investigated a major issue: the stability of mixed layers as a function of composition. We also conducted second harmonic generation and surface plasmon enhanced electrooptic modulation in mono and multi-layer Langmuir-Blodgett films.

Our group conducted both theoretical and experimental studies of photorefractivity in multifunctional polymeric materials. Photorefractive effect was observed in a fullerene (C_{60}) doped organic composite containing polyvinylcarbazole (PVK) and a second-order active molecule, diethylamino nitrostyrene (DEANST) and in a nonlinear organic polymer doped with a photosensitizer BDK and a hole transport agent tri-p-tolylamine.

New $\chi^{(2)}$ Materials

We have made significant progress on developing novel nonlinear molecular materials which do not rely on π-electron conjugation to produce large second-order effects. Crystals of the 1:3 complex between antimony triiodide and sulfur $SbI_3{}^*3S_8$ were found to possess a high second order optical nonlinearity. The powder second harmonic generation efficiency was found to be approximately half of that of isostructural complex of iodoform with sulfur $CHI_3{}^*3S_8$. Second harmonic generation can be phase matched. The phase matching angle of type I was found to be approximately 30 degrees at the fundamental wavelength 1.064 μm. The Maker fringes measurements gave $\chi_{222}^{(2)} \approx 16$ pm/V, $\chi_{333}^{(2)} \approx 23$ pm/V and $\chi_{311}^{(2)} \approx 15$ pm/V for the values of the components of the second order susceptibility tensor. The third rank hyperpolarizability tensor β was decomposed into irreducible parts, the norms of the vector part and the septor (octupolar) part in the $SbI_3{}^*3S_8$ complex were evaluated to be $\beta_v = 52.1\times10^{-40}m^4/V$, $\beta_s = 20.2\times10^{-40}m^4/V$.

Langmuir-Blodgett Films

Langmuir-Blodgett films provide a unique opportunity to prepare novel molecular assemblies for nonlinear optics. Stability and good structural correlation in multilayer Langmuir-Blodgett films are important issues. Our work focussed on studying the stability of mixed layers as well as on studying the second harmonic generation and surface plasmon electro-optic modulation in Langmuir-Blodgett films. The surface pressure π of two component monolayers of stearic acid (SA) and 3,4-didecyloxy-2,5-di(4-nitrophenylazomethine) thiophene (DNAT) was measured at the air-water interface by the Wilhelmy method as a function of mean molecular area at various compositions. The surface properties of these mixed films were interpreted in terms of both the additivity rule of molecular areas and the two-dimensional phase rule applied to collapse pressures. Results indicate that SA is miscible with DNAT to up to $\chi_{SA} > 0.5$. At $\chi_{SA} > 0.5$ phase separation occurs and at $\pi > 14$ mN m^{-1} DNAT is ejected from the highly ordered SA film matrix. The index of refraction and thickness of these films dielectrics were determined through surface plasmon (SP) measurements on approximately 500 Å thick silver substrates. Horizontal lifting was used to transfer the Langmuir-Blodgett monolayers to glass slides coated with silver. Mixed solid films of DNAT up to 10% (by weight) in polystyrene matrices with thicknesses ranging from 4 to 12 μm were also prepared, indices and thicknesses being measured using the m-line technique. This allowed us to estimate the index of pure DNAT as a cross-check on the SP results. Since index determinations from these techniques are in essential agreement in terms of linear refractivity, we are able to discuss the structural implications of the SP-measured monolayer film thicknesses.

Second harmonic generation (SHG) and surface plasmon studies were carried out on mono- and multilayer Langmuir-Blodgett (LB) films of an amphiphile containing a small chromophore (*N*-docosanoyl-4-nitroaniline). A quadratic variation in the second harmonic intensity was observed for Y-type multilayers (film thickness above 4 bilayers), but for the thinner films (film thickness less than 4 bilayers) the enhancement of the SHG intensity does not follow the quadratic dependence. The results indicate that the non-linear chromophores lie almost flat on the plane of the substrate with orientation preference in the dipping direction. The SHG behavior and the second-order nonlinearity of the LB films were compared with those of 2-docosylamino-5-nitropyridine and *N*-docosyl-4-nitroaniline which also have a chromophore of similar size.

Measurements of electrooptic modulation of surface plasmon resonance were carried out on horizontally transferred Langmuir-Blodgett films of 2-docosylamino-5-nitropyridine. The observed Pockels response is approximately constant for different numbers of layers in multilayered films and is proportional to the strength of the modulating field. The calculated second order susceptibility values are about 2×10^{-13} m/V, two orders of magnitude lower than those derived from second harmonic generation studies. The presence of the Pockels effect was attributed to off-diagonal terms in the second order susceptibility.

Second harmonic generation (SHG) studies were carried out on Langmuir-Blodgett films of 2-docosylamino-5-nitropyridine which were transferred using two different dipping techniques; vertical Y-type and horizontal X-type depositions. The SHG behavior of both types of films can be explained by assuming an average planar symmetry. However, the SHG behavior of horizontally transferred films is remarkably different from that of the vertically transferred films. In Y-type films the SHG is mainly due to the in-plane component $\chi^{(2)}_{yyy}$ (which is along the dipping axis) of the second order nonlinear optical susceptibility tensor and $\chi^{(2)}_{xxx}$ is negligible. In the case of X-type films, also, the SHG is due to the in-plane $\chi^{(2)}$ tensor components but $\chi^{(2)}_{yyy}$ and $\chi^{(2)}_{xxx}$ have comparable magnitudes. In both films the nonlinear optical chromophores lie almost flat with respect to the plane of the substrate. The cancellation of $\chi^{(2)}_{xxx}$ in Y-type films is due to the preferential orientation of molecular domains along the dipping axis. In horizontally transferred films molecular domains seem to be inhomogeneously oriented on the surface.

Sol-Gel Processed Composites for $\chi^{(2)}$

Sol-gel processing was used to prepare a new class of multicomponent inorganic oxide:organic polymer composites which show great promises for second-order nonlinear optics. Special processing technique has permitted the preparation of SiO_2/TiO_2/organic polymer composites in which the relative composition can be judiciously varied to select the linear refractive index for applications in integrated optics. Furthermore, this composite has been

doped with both inorganic and organic dopants. The composite film doped with paranitroaniline (PNA) was successfully poled. Both second-harmonic generation and electrooptic modulation were achieved in such a poled four-component SiO_2/TiO_2/Polymer/PNA composite.

Sol-gel processing technique was also used to prepare a composite with second-order nonlinear optically active molecule, N-(4-nitrophenyl)-(s)-prolinol. Electric-field poling was successfully employed to introduce noncentrosymmetry required for second-order nonlinearity. Studies using *in situ* poling allowed the formulation of conditions under which stable poled orientation was achieved. Second-harmonic generation and electro-optic modulation studies were conducted on this material.

Diethylaminonitrostyrene (DEANST) was doped into different polymer matrices with extremely high concentrations (up to 70% by weight) without loss of optical quality. The polymers used include PMMA and polyvinylcarbazole. The $\chi^{(2)}$ values obtained are over 10^{-7} esu.

We have also successfully prepared composites of DEANST doped with the sol-gel processed silica and TiO_2. The electric field poling procedure was modified in order to achieve the best conditions for the largest obtainable second-order nonlinearity. Temporally and thermally stable $\chi^{(2)}$ values of up to 2×10^{-7} esu have been obtained. An additional means toward enhancing stability of poled structures is the combination of the sol-gel technique with the thermal-induced crosslinking of polymers. This combination of techniques further reduces the rotational freedom for the NLO dopants inside the matrix. It also improved other properties of the material composite, such as mechanical and electrical properties.

Because of the strong solvatochromic effect observed in the chromophore, we are able, using matrices with low dielectric coefficient, to shift the absorption band to shorter wavelength spectral range. This is important for avoiding the reabsorption of the light from second-harmonic generation (wider optical transparency).

Novel Molecular-Ionic Polymers for $\chi^{(2)}$.

To take advantage of nonlinearities derived from both molecular and ionic contributions new methacrylate polymers containing the N-alkyl pyridinium salt in the side chain were designed and synthesized. Even though these structures contain counter-ions which can migrate under the influence of applied field, we were successful in poling. The corona poled polymer films showed a large second-order nonlinear optical susceptibility, $\chi^{(2)}$ $(-2\omega;\omega,\omega)$. The larger $\chi^{(2)}$ value of the homopolymer containing N-methylpyridinium salt, compared to that of its copolymer, indicates that the concentration of the nonlinear optical chromophores in the copolymer is lower than the saturation value. The temporal stability of induced alignment of

nonlinear optical chromophore seems better than that of many other side-chain polymers and guest-host systems.

In order to enhance the poling efficiency by reducing the prospect of charge migration the small counter-ion (I^- or Br^-) of the salt unit was substituted by a bulky tetraphenylborate (TPB) ion. The corona poled polymer film showed a large second-order nonlinear optical susceptibility, $\chi^{(2)}(-2\omega;\omega,\omega)$. The larger $\chi^{(2)}$ values of these polymers were compared with that of polymer with small counter-ion. It was found that the organoborate unit at the side chain improved the optical quality of the polymeric film compared to the polymer having a small organic counter-ion. Even their monomers could be deposited as a transparent layer on a glass substrate. The temporal stability of the polymer without internal side chain spacer unit was investigated to be better than those of the other polymers with six and ten methylene spacer. Above all, the temporal stability of induced alignment of nonlinear optical chromophore in this TPB series of polymer seems to be better than that of many other side-chain polymers and guest-host systems.

Use of composite structures for improvement of bulk optical quality

We reported here the first case (to our knowledge) of a compatible blend between an inorganic polymer, silica glass, and a π-conjugated optical nonlinear polymer, poly (p-phenylene vinylene), homogeneously mixed over large composition ranges. This composite material was prepared by combining sol-gel processing techniques applicable to the silica glass with the preparation of the organic polymer from a water/alcohol soluble sulfonium salt precursor. The organic polymer precursor and the inorganic sol were mixed in a common solvent and converted to the final composite material. The thermal conversion of the organic precursor polymer released HCl which also catalyzed the gelation of the inorganic sol. The composite material was characterized by IR, UV-visible spectral analysis and thermogravimetric and differential scanning calorimetric analysis. The material can be cast into various forms. Thin films cast by the doctor blading technique exhibit good optical quality and show promise for application in the form of optical wave guides.

The approach used for sol-gel optics i.e. the use of sol-gel processing can play a very important role for the development of novel materials and device structures for nonlinear optics and photonics. Chemical processing using the sol-gel method was used for preparation of new composite materials of both a silica glass and a V_2O_5 gel with a π conjugated polymer poly-p-phenylene vinylene up to 50% by weight. The composite films show highly improved optical quality with large third-order nonlinear optical coefficient, the latter derived from the conjugated polymer. Optical waveguiding through the film has been achieved. Nonlinear optical studies using femtosecond degenerate four wave mixing, optical Kerr gate switching and power dependent waveguide coupling have been successfully performed.

A two-dimensional permanent transmission grating was formed on the novel polymer sol-gel composite film by ultrashort (~0.5-ps) and visible (~602-nm) pulsed laser radiation. With an arrangement of three nonco-planar coherent laser beams, we used two approaches to produce direct formation of a two-dimensional grating on the film. One approach is to expose the sample twice to different combinations of two beams, and the other is to expose the sample to three laser beams simultaneously. The diffraction patterns and the relative intensity distributions for different order diffraction of the two-dimensional gratings formed on the poly-p-phenylene vinylene/V_2O_5-gel films are analyzed for the different two-beam combinations and relative orientations among the three laser beams. The total diffraction efficiency for the incident probe laser beam into all the non-zero-order diffraction beams reaches 48%.

Femtosecond response and relaxation of the third order optical nonlinearity in the newly developed poly(p-phenylene vinylene)/sol-gel silica composite were investigated by time-resolved forward wave degenerate four-wave mixing, Kerr gate and transient absorption techniques using 60 femtosecond pulses at 620 nm. Using a theoretical description of two and four-wave mixing in optically nonlinear media it is shown that the results obtained from simultaneous use of these techniques yield valuable information on the real and imaginary components of the third order susceptibility. In the composite material investigated here, the imaginary component is derived from the presence of a two-photon resonance at the wavelength of 620 nm used for the present study. This two-photon resonance is observed as transient absorption of the probe beam induced by the presence of a strong pump beam. It also provides fifth-order nonlinear response both in transient absorption and in degenerate four-wave mixing. The fifth-order contributions are derived from the two-photon generated excited species which can absorb at the measurement wavelength and therefore modify both the absorption coefficient and the refractive index of the medium.

Study of photorefractivity in polymers

Our group started both theoretical and experimental studies of photorefractivity in polymeric systems. For photorefractivity, when a photoconducting polymer is illuminated by light with an intensity that varies sinusoidally with position, the space-charge electric field, hole density, ionized photosensitizer density, and filled hole trap density will also vary with position. Expressions were derived for the zero-order Fourier component of the hole density and the first-order Fourier component of the electric field. The equations take into account the electric field dependence of photocharge generation efficiency and mobility. General equations were simplified for the case in which the trap density is far greater than the density of holes, and for the case in which no hole traps are present. Finally, the zero-order hole density and first-order electric field calculated from our equations were compared to values obtained by Fourier transforming the results of numerical calculations.

Photorefractive effect was observed in a fullerene (C_{60}) doped organic composite containing poly-vinylcarbazole (PVK) and a second-order molecule, diethyl-amino-nitrostyrene (DEANST). Electrooptic modulation and degenerate four-wave mixing experiments were conducted. The material shows relatively high electrooptic coefficient, photoconductivity quantum efficiency and photorefractive diffraction efficiency.

We also reported an experimental observation of the photorefractive effect in a new polymeric system in which a nonlinear organic polymer was doped with a photosensitizer BDK and a hole transport agent tri-p-tolylamine. The photoconductivity and the electro-optic effect have been studied. The process of the grating formation with the applied field was studied. A strong electric field dependence of the diffraction coefficient has been observed.

For the C_{60}:PVK:DEANST composite, a theory of space charge-field grating formation for photoconductive polymers was used to calculate the four-wave mixing diffraction efficiency. Holes were assumed to be the dominant charge carriers and the field dependencies for both photocharge generation and charge carrier mobility were considered. A satisfactory agreement between the theoretical model and the experimental results was obtained. The dependence of the diffraction efficiency on the grating slant angle, as well as the difference between the two fundamental s- and p-polarized readouts were investigated. We showed that the poling-induced anisotropy of the second-order nonlinear optical activity and the birefringence of the medium have a strong influence on the angular dependence of the diffraction efficiency.

Our recent studies on improved samples have yielded very high diffraction efficiencies up to 40% and an asymmetric two-beam coupling gain of 130 cm^{-1}. These values compare very favorably with those of e.g., $BaTiO_3$. We have also conducted an investigation of the kinetics of grating buildup and decay induced optically and with electric field. The optical response time at ~1 watt/cm^2 is less than 0.1 sec.

PUBLICATIONS RESULTING FROM CURRENT BMDO/AFOSR SUPPORT

1. "Sol-Gel Processed Novel Multicomponent Inorganic Oxide:Organic Polymer Composites for Nonlinear Optics", Y. Zhang, Y. P. Cui, C. J. Wung, P. N. Prasad and R. Burzynski, SPIE Proceedings, Vol. 1560, 264, (1991).
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3. "Sol-Gel Processed Inorganic and Organically Modified Composites for Nonlinear Optics and Photonics" in Advanced Composite Materials, American Ceramic Society publication, Ed. M. Sachs (1991) p. 279.
4. "Two-Dimensional Optical Grating Produced on PPV/V_2O_5-Gel Film by Ultrashort Pulsed Laser Radiation", G. S. He, C. J. Wung, G. C. Xu and P. N. Prasad, Appl. Opt. 30, 3810-3817 (1991).
5. "Third Order Nonlinearity and Two Photon-Induced Molecular Dynamics: Femtosecond Time Resolved Transient Absorption, Kerr Gate and Degenerate Four-Wave Mixing Studies in Poly(p-phenylene vinylene)/Sol-Gel Silica Film", Y. Pang, M. Samoc and P. N. Prasad, J. Chem. Phys. 94, 5282 (1991).
6. "Polymeric Materials for Nonlinear Optics and Photonics", P. N. Prasad, Polymer 32, 1746-1751 (1991).
7. "Photonics and Nonlinear Optics-Materials and Devices" in "Lower-Dimensional Systems and Molecular Devices", Ed. R. M. Metzger, Plenum Press, New York (1991) p. 563-572.
8. "Langmuir-Blodgett Films for Nonlinear Optics" in "Lower-Dimensional Systems and Molecular Devices", Ed. R. M. Metzger, Plenum Press, New York (1991) p. 573-577.
9. "Temporal Behavior of Stimulated Kerr Scattering in a CS_2 Liquid-core Hollow Fiber System", G. S. He, G. C. Yu, Y. Pang and P. N. Prasad, J. Opt. Soc. Am. B. 8, 1907-1913 (1991).
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12. "Linear and Nonlinear Optical Studies of Mono- and Multilayer Langmuir-Blodgett Films of N-docosanoyl para-nitroaniline", W. M. K. P. Wijekoon, B. Asgharian, P. N. Prasad, T. Giesler and S. Rosenkilde, Thin Solid Films 208, 137 (1992).

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15. "Electro-Optic Effect in Langmuir-Blodgett Films of 2-Docosylamino-5-nitropyridine Probed by Surface Plasmon Waves", W. M. K. P. Wijekoon, B. Asgharian, M. Casstevens, M. Samoc, G. B. Talapatra, P. N. Prasad, T. Giesler and S. Rosenkilde, Langmuir 8, 135 (1992).

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17. "Second-Order Nonlinear Optical Properties of N-(4-Nitrophenyl)-(S)-Prolinol-Doped Sol-Gel Processed Materials", Y. Zhang, P. N. Prasad and R. Burzynski, Chem. Mat. 4, 851 (1992).

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25. "Polymers for Photonic Applications", K. S. Lee, M. Samoc, and P. N. Prasad, Comprehensive Polymer Science, Eds. S. L. Agarwal and S. Russo, Pergamon Press (Oxford, 1992) p. 407.

26. "Strategy for Optimization of Molecular and Polymeric Materials For Nonlinear Optics", P. N. Prasad in "Nonlinear Optics - Fundamentals, Materials and Devices", Ed. S. Miyata, Elsevier Science Publishers (Amsterdam, 1992) p. 283.

27. "Sol-Gel Processed Inorganic Oxide:Organic Polymer Composites for Second-Order Nonlinear Optics Applications" J. Zieba, Y. Zhang and P. N. Prasad, SPIE Proceedings on Sol-Gel Optics II, Ed. J. D. Mackenzie, 1758, 403-409 (1992).

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35. "Zero-Order and First-Order Theory of the Formation of Space-Charge Gratings in Photoconductive Polymers", J. S. Schildkraut and Y. Cui, J. Appl. Phys. (in Press).

36. P. N. Prasad, "Nonlinear Optical Effects in Polymer Electrodes and Sol-gel Processed Glass", IEEE Trans. on Dielectrics and Electrical Insulation 1, 585 (1994).

INVITED TALKS ON RESEARCH SUPPORTED BY BMDO/AFOSR

1. Pennsylvania State University, Department of Chemistry, April 2, 1991.
   "Polymers and Photonics - A New Frontier of Science and Technology".

2. 150th Annual Chemical Congress of the Royal Society of Chemistry, Symposium on New Electronic Materials, London, U.K., April 11, 1991.
   "Molecular and Polymeric Materials for Nonlinear Optics and Photonics".

3. Hoechst-Celanese, Summit, N.J., April 23, 1991.
   "Nonlinear Optics and Photonics with Novel Molecular Composites".

4. Enichem of America, Princeton, N.J., April 24, 1991.
   "Nonlinear Optics and Photonics with Novel Molecular Composites".

5. Case Western Reserve University, Department of Macromolecular Science, Cleveland, OH, April 26, 1991.
   "Polymers and Photonics - A New Frontier of Science and Technology".

6. CLEO '91, Baltimore, MD, May 14, 1991. Tutorial Lecture on
   "Nonlinear Optics with Organic Materials".

7. University of Washington, Department of Materials Science, Seattle, WA, May 20, 1991.
   "Novel Sol-Gel Processed Inorganic Oxide: Polymer Composite Materials for Photonics".

8. "Nonlinear Optics Summer School, Rochester, NY, June 12, 1991. Tutorial Course
   "Nonlinear Optical Materials".

9. SPIE - The International Society for Optical Engineering Meeting, San Diego, CA, July 23, 1991. Tutorial Lecture on:
   "Introduction to Nonlinear Optical Materials".

10. SPIE - The International Society for Optical Engineering Meeting, San Diego, CA, July 25, 1991 - chaired a session.

11. Korea University, Department of Chemistry, Seoul, KOREA, July 29, 1991.
    "Nonlinear Optical Processes in Conjugated Polymers".

12. Korea Institute of Science and Technology (KIST), Seoul, KOREA, July 29, 1991.
    "Polymeric and Composite Materials for Nonlinear Optics and Photonics".

13. Tongyang Nylon Company, Kyungi-DO, KOREA, July 30, 1991.
    "Polymeric and Composite Materials for Nonlinear Optics and Photonics".

14. Samsung Electronics, Kyung Ki-DO, KOREA, July 30, 1991.
"Polymeric and Composite Materials for Electronics and Photonics".

15. Korean Research Institute of Chemical Technology (KRICT), Taejon, KOREA, July 31, 1991.
"Recent Advances in Polymeric and Composite Materials for Nonlinear Optics".

16. Lucky Ltd., R & D Center, Taejon, KOREA, July 31, 1991.
"Polymeric and Composite Materials for Photonics and Electronics".

17. Pohang Institute of Science and Technology (POSTECH), Department of Materials Science, Pohang, KOREA, August 1, 1991.
"Nonlinear Optical Effects in Molecules and Polymers".

18. Hoechst Japan, Tokyo, JAPAN, August 9, 1991.
"Polymeric and Composite Materials for Photonics and Electronics".

19. Tokyo University of Agriculture and Technology, Materials Systems Engineering Department, Tokyo, JAPAN, August 10, 1991.
"Polymeric and Composite Materials for Nonlinear Optics".

20. US-UK Optical Glass and Macromolecular Materials Workshop, Ilkey, U.K., August 20, 1991.
"Strategy for Optimization of Molecular and Polymeric Materials for Photonics".

21. Northern Illinois University, Department of Chemistry, DeKalb, Illinois, September 9, 1991.
"Nonlinear Optical Processes in Molecular and Polymeric Materials".

22. Fifth Toyota Conference on Nonlinear Optical Materials, Nissin, JAPAN, October 9, 1991.
"Strategy for Optimization of Molecular and Polymeric Materials for Nonlinear Optics".

23. First International Conference on NLO Active Materials, Tokyo, JAPAN, October 11, 1991.
"Composite Materials for Nonlinear Optics".

24. Nonlinear Optics - Materials, Methods and Components, Stockholm, SWEDEN, October 22, 1991.
"Nonlinear Optics and Photonics with Molecular, Polymeric and Composite Materials - An Overview".

25. Second ALCOM Symposium, Akron, Ohio, November 6, 1991.
"Photonics and Nonlinear Optics: An Overview".

26. Materials Research Society Fall Meeting, Symposium on Hierarchically Structured Materials, Boston, Massachusetts, December 4, 1991.
"Nonlinear Optical Properties of Hierarchical Systems".

27. Air Force Contractors NLO Meeting, Dayton, Ohio, December 9, 1991.
"Strategy for Optimization of Molecular, Polymeric and Composite Materials for Nonlinear Optics and Photonics".

28. US-India Workshop on Frontiers of Research in Polymers and Advanced Materials, Goa, INDIA, January 8, 1992.
"Molecular Materials and Structure-Property Relationship for Photonics".

29. SPIE - The International Society for Optical Engineering Meeting, Los Angeles, CA, January 22, 1992 – chaired a session on Nonlinear Optics.

30. University of Alabama, Department of Chemistry, Tuscaloosa, Alabama, February 21, 1992.
"Nonlinear Optical Effects in Molecules and Polymers".

31. Lubrizol Corporation, Ohio, February 26, 1992.
"Electroactive Polymers – Issues, Opportunities and Role of Computational Chemistry".

32. Case Western Reserve University, Department of Chemistry, February 27, 1992.
"Nonlinear Optical Effects in Molecules and Polymers".

33. State University of New York at Stony Brook, Department of Chemistry, March 20, 1992.
"Chemistry and Photonics – A New Frontier of Science and Technology".

34. CLEO '92, Anaheim, CA, May 10, 1992. Tutorial Lecture on
"Nonlinear Optics with Organic Materials".

35. AFOSR Computational Chemistry Workshop, Dayton, Ohio, May 19, 1992.
"Computational Chemistry and Nonlinear Optics – Current Status and Future Directions".

36. 34th IUPAC International Symposium on Macromolecules, Prague, Czechoslovakia, July 14, 1992.
"Nonlinear Optical Processes in Polymers".

37. Nonlinear Optics Summer School, Rochester, NY, July 17, 1992. Tutorial Course:
"Nonlinear Optical Materials".

38. US-UK Optical Glass and Macromolecular Materials Workshop, San Diego, CA, July 18, 1992.
"Heterostructures and Composites for Nonlinear Optics".

39. SPIE – The International Society for Optical Engineers Meeting, San Diego, CA. Symposium on Sol-Gel Optics II, July 21, 1992.
"Novel Sol-Gel Processed Multicomponent Inorganic Oxide:Organic Composite Materials for Nonlinear Optics and Photonics".

40. Gordon Research Conference on Electronic Processes in Orgar lids, Andover, NH, July 30, 1992.
"Nonlinear Optical Effects in Molecular, Polymeric, and C posite Materials".

41. 3rd International Symposium on Organic Materials for Nonlinear Optics, OMNO 92, Oxford, U.K., August 21, 1992.
"Recent Advances in Polymeric and Composite Materials for Nonlinear Optics".

42. PPG Industries, Inc., Chemicals Group Technical Center, Monroeville, PA, October 12, 1992.
"Non-linear Optics with Molecular Materials".

43. Second International Conference on Frontiers of Polymers and Advanced Materials, Jakarta, INDONESIA, January 12, 1993.
"Novel Polymeric Composite Materials for Photonics".

44. SPIE Sponsored NTU Satellite Course, March 18, 1993
"Introduction to Nonlinear Optical Materials".

45. American Chemical Society National Meeting, Denver, CO., March 30, 1993.
"Nonlinear Optical Properties of Novel Glassy Phase Composites".

46. University of Michigan, Department of Chemistry, Ann Arbor, MI., April 15, 1993.
"Nonlinear Optical Effects in Molecules and Polymers".

47. 6th OGAMM Meeting, Los Angeles, CA, July 8, 1993.
"Multifunctional Organic Heterostructures for Electro-Optics Applications".

48. SPIE Meeting, San Diego, CA, July 12, 1993. Symposium on Nonlinear Optical Properties of Organic Materials.
"Photorefractivity in Polymeric Composite Materials".

49. Nonlinear Optics Summer School, Rochester, NY, July 18, 1993, Tutorial Course.
"Nonlinear Optical Materials".

50. University of Hyderabad, School of Physics, Hyderabad, India, August 6, 1993.
"Nonlinear Optical Processes in Organic Molecules and Polymers".

51. Second International School and Topical Meeting on Applications of Nonlinear Optics, Prague, Czech Republic, August 16, 1993.
"Nonlinear Optics of Novel Organic and Polymeric Materials".

52. BASF, Ludwigshafen, Germany, August 19, 1993.
"Novel Trends in the Field of Molecular, Polymeric and Composite Materials for Nonlinear Optics".

53. American Chemical Society, National Meeting, Polymer Chemistry Symposium on Marvel Award, August 24, 1993.
"Novel Polymeric Composites for Photonics".

54. 2nd Brazilian Polymer Conference, Sao Paulo, Brazil, October 6, 1993.
"Polymers for Photonics".

55. A series of five lectures at Telebras, the telecommunication company of Brazil, Campinas, Brazil, October 8-14, 1993.
Titles:
(i) Organic and Polymeric Materials for Nonlinear Optics and Photonics: An Overview.
(ii) Measurements and Characterization Techniques for Second-Order Processes.
(iii) Molecular Engineering and Materials Processing for Electro-Optic Devices.
(iv) Waveguides, Interconnects and Electro-Optics Devices.
(v) Current Status, New Trends and Future Directions for Materials and Applications for Electro-Optics and Photorefractivity.

56. Polymer Conference, Cancun, Mexico, November 3, 1993.
"Novel Polymeric Composite Materials for Nonlinear Optics and Photonics".

57. SPIE Meeting Los Angeles, California, January 24, 1994.
"Polymeric Composite Photorefractive Materials for Nonlinear Optical Applications".

58. Thirty-Fourth Sanibel Symposium, Ponte Vedra Beach, Florida, February 18, 1994.
"Nonlinear Optical Effects in Molecules and Polymers: Issues and Opportunities".